Electron beam experiments at FAST

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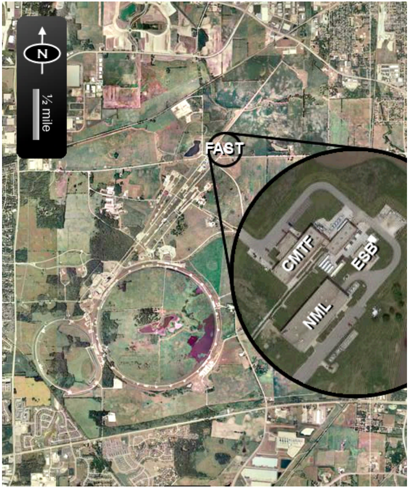
July 17, 2018

Outline

1. FAST electron photoinjector
   - Facility and beamline overview
   - 1.3 GHz SRF cavity transfer map measurement
2. Microlens array laser shaper
   - Laser transverse shaping, emittance reduction
   - Multi-beam generation and applications
3. CAM and flat beam generation
   - CAM beams formation
   - Flat beam generation and emittance measurements
4. Longitudinal space-charge amplifier

FAST introduction



Fermilab Accelerator Science and Technology - FAST

- 300 MeV electrons
- Linac + Ring
- End of construction - late 2018

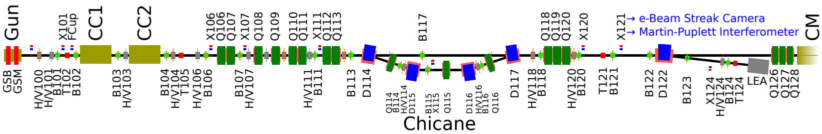
`http://fast.fnal.gov/`

FAST injector + IOTA ring

ILC-type cryomodule - Picture is courtesy of FAST

- Cs_2:Te photocathode + 1.3 GHz RF gun
- Two 1.3 GHz SRF capture cavities + cryomodule = 300 MeV
- Injection into IOTA ring (150 MeV) + high energy electron beam experiments (X-ray channeling, ICS, flat beams)

Electron injector



2015 (20 Mev) → 2016 (52 Mev) → 2017 (301 MeV)

2018 Ring completion / Experimental program start

- Charge range: 10 fC - 3.2 nC per pulse (up to 3000 pulses/s)
- Nominal bunch length: 5 ps (minimum: 2 ps)
- Magnetic chicane and skew-quadrupole adapter (RTFB)
- Includes interaction points for medium (50 MeV) and high (300 MeV) energies, multislits, goniometer, pyro, etc.

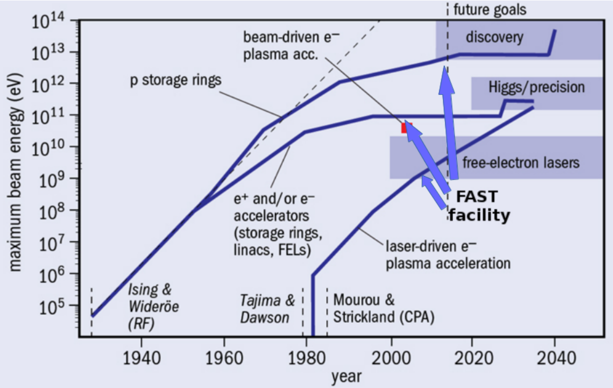
Detailed description: Antipov, S., *et al*, JINST, **12**, T03002 (2017)

Electron beam parameters

Parameter	Value	Units
Emittance (norm.)	0.7	μm
Beam energy	50 - 300	MeV
Slice energy spread	$<$5	keV
Nominal charge	250	pC
Bunch length	5	ps
Beta-function (CC2 exit)	8	m
Dipole bending radius	0.958	m
Dipole length	0.301	m
Dipole angle	18	degrees
R_{56}	-0.18	m

Beam-based alignment: Romanov, A., arXiv:1703.09757 [physics.acc-ph]

Motivation for Research



Livingston plot - Image courtesy of CERN

How does electron beam research contribute to the field?

Dissertation Impact

What we wanted to do:

Electron beam transverse and longitudinal shaping in a photoinjector

Why:

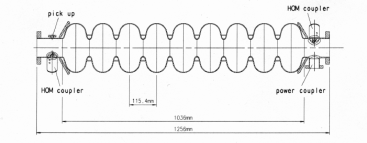
1. Understand and improve beam dynamics at FAST
2. Implement transverse laser shaper, improve emittance
3. Perform Round-to-Flat beam transform
4. Consider space charge amplifier at FAST

FAST - Fermilab Accelerator Science and Technology facility

http://fast.fnal.gov/

1.3 GHz SRF accelerating cavity

Beam dynamics of FAST low energy beamline defined by:

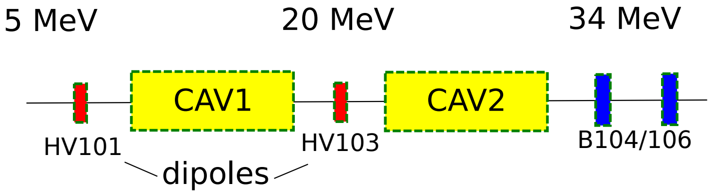


Several proposed or operating accelerator facilities include TESLA-type cavities, such as FAST, ILC, LCLS-II, PIP2 and etc. to accelerate electron, proton or muon beams

1. Experimentally verify Chambers-Serafini-Rosenzweig model
2. Attempt to characterize the effects of couplers

Experimental setup (2016)

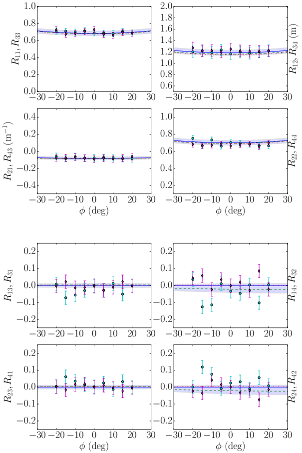
Schematics of the experiment

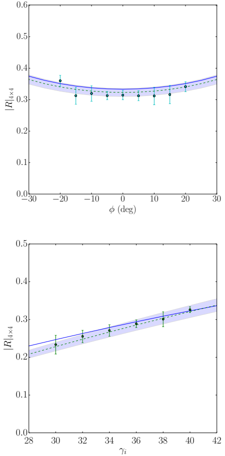


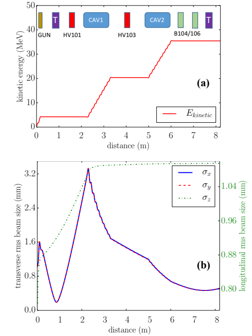
Experiment details

1. Diagnostics/controls automatic (Piot, Halavanau (NAPAC16))
2. Possible to vary injection energy (use CAV1, measure CAV2)
3. Reference orbit method; R inverted with least squares
4. Strong focusing in CAV1 (alters beam quality)
5. Instrumentation (BPM jitter $<$ 80 um), laser

Results







Each data point is inferred from 80 reference orbits

(left) transfer matrix R elements; (middle) determinant $R_{4\times4}$ as a funciton of phase (ϕ) and injected γ_i; (right) beam dynamics in low energy section.

Cavity transport summary

Conclusions:

- Chambers' model is accurate at FAST energies ($>$34 MeV)
- HOM effect - phase dependent parametric dipole kick

Outcomes:

- Beam-based alignment can be done via minimization procedure (experimentally confirmed for CG/BFGS-methods)
- Better understanding of low energy round beam dynamics, helps with flat beam
- Improved analytical linear model of linac (used for 300 MeV comissioning)
- Tools (pyACL, beam-based alignment)

Halavanau, A., Phys. Rev. Accel. Beams ***20****, 040102 (2017)*

Emittance studies

Nominal FAST electron beam norm. emittance $\epsilon = 0.7\mu$m at comissioning charge of Q=250 pC (small laser spot + optimization)

Available measurement techniques:

1. Quadrupole scan (automatic)
2. Horizontal/vertical multislits
3. Possible to install pepper-pot

FAST electron beam norm. emittance at fully opened laser iris $\epsilon = 1.9\mu$m ($\sigma \approx 1$mm)

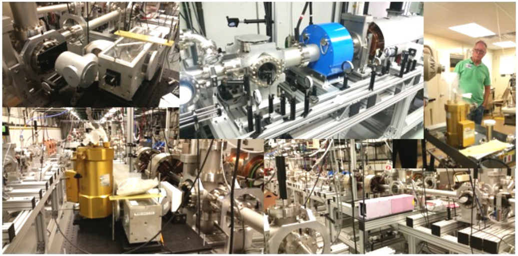
How to reduce emittance by x2?

$$\epsilon =< \sigma_\perp^2 >^{1/2} < \Delta\theta_\perp^2 >^{1/2}, \qquad \Delta\theta_\perp^2 = \mathcal{F}(T_{eff} + F_i + F_{SC})$$

F_{SC} can be linearized in the case of transverse uniform distribution

Laser can be homogenized by Microlens Arrays (MLAs)

Inspiration: bumpy ceiling light cover

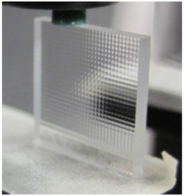


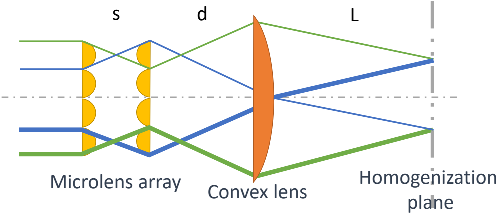
72 MeV photoinjector + EEX beamline. Proof-of-principle MLA shaping experiment, emittance reduction by factor of 2, comissioned and used for experiments at AWA

Microlens arrays (MLAs)

In photocathodes the achievable electron beam parameters are controlled by the laser used to trigger the photoemission.

Microlens arrays are fly-eye type light condensers



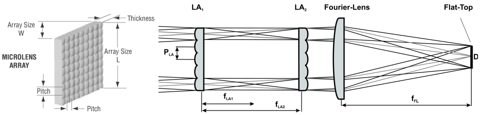


1. Produce uniform laser image in the focal plane of the mixing lens
2. Produce transversely modulated laser beams

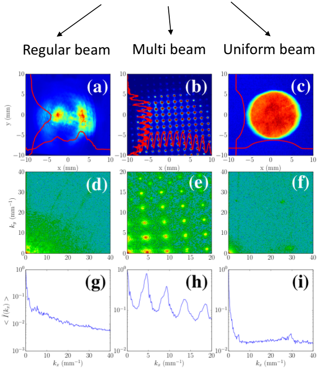
Microlens array setup

1. Homogenized/Patterned beam can be imaged (4 lens solution)
2. Can produce high intensity beams
3. Hexagonal lattice for best homogenization

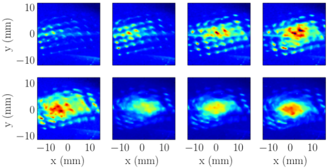
Microlens array (MLA) setup at AWA



AWA UV laser



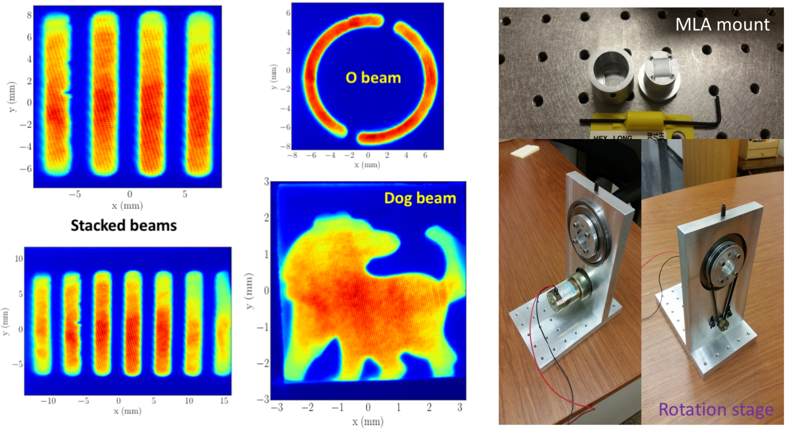
Multi beam at 50 MeV



Halavanau, et. al, Phys.Rev.Accel.Beams 20 (2017), 103404

MLA laser shaper

Arbitrary laser transverse profile: homogenizer + mask

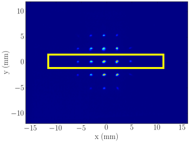


MLAs were mounted on a rotation stage; pinhole

Emittance exchange setup

1. Use MLA to produce multi-beams
2. Send multi-beam through EEX and generate bunch trains
3. Use MLA rotation for bunch train tuning

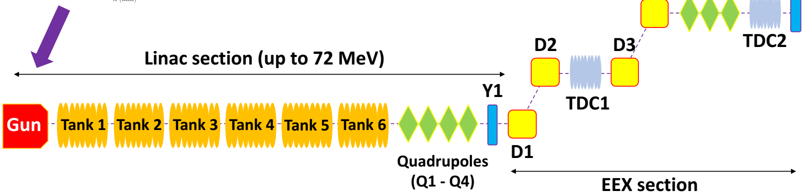
Experiment schematics: (MLA + EEX)



Goal: Combine MLA multi-beams with EEX to generate bunch trains

- MLA setup can shape laser spot to create multi-beams
- Additionally, a line of laser dots can be selected

Benefits:
- Easy to implement
- Variable array size / spacing / rotation angle



In progress, reported at IPAC18

Microlens array summary

1. Generated homogenized and patterned beams with a single setup (elegant and simple)
2. Comissioned and used routinely at AWA
3. Application in photocathode quantum efficiency measurement (**NEW, in progress**)
4. Application in bunch train generation (**NEW, in progress**)
5. Implementation at FAST underway
6. Interest of SLAC, UCLA, LBNL, PITZ and many others

Why magnetized beams?

Canonical angular momentum (CAM) dominated beams:

1. Conventional application - electron cooling (Derbenev, Ya., UM-HE-98-04-A)
2. Emittance partitioning via flat beams (interest of AWA group)
3. Flat beams in plasma acceleration (interest of UCLA/AWA)
4. Flat beams in DLWA (interest of PEGASUS facility)
5. Supressing microbunching instabilities in IOTA (collaboration with R. Li, JLab)
6. Several possible radiation experiments (dielectric structures, microundulators, channeling, etc.) can be done at FAST

CAM beams production at FAST is a stepping stone

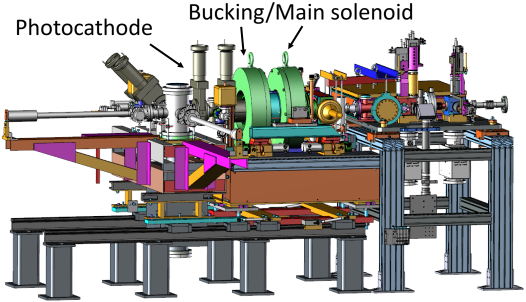
Busch's theorem

Total canonical angular momentum
of a charged particle in symmetric magnetic field is conserved

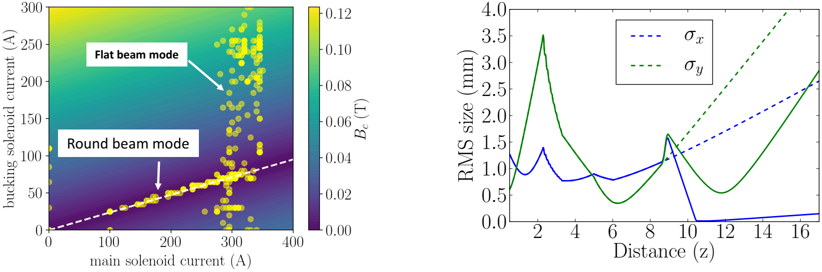
$$L = \gamma m r^2 \dot{\theta} + \frac{1}{2} e B_z(z) r^2 \qquad \mathcal{L} = L/2p_z$$

Eigenemittances:

$$\epsilon_{\pm} = \sqrt{\epsilon_u^2 + \mathcal{L}^2} \pm \mathcal{L} \rightarrow \quad \epsilon_{+} \approx 2\mathcal{L}; \quad \epsilon_{-} \approx \frac{\epsilon_u^2}{2\mathcal{L}}$$



CAM and flat beam dynamics



1. Two gun solenoids must ensure full transmission → can't wire them opposite (in that case max B_z=0.2 Tesla)
2. In our experiment B_z=0.07 Tesla was selected (after solenoid optimizations)
3. Dash/solid lines represent magnetized/flat beam RMS size

Emittance ratio

Eigenemittances:

$$\epsilon_- \equiv -\sqrt{\epsilon_0^2 + \mathcal{L}^2 - 2\mathcal{L}\epsilon_0} = -\sqrt{(\epsilon_0 - \mathcal{L})^2} = \mathcal{L} - \sqrt{\mathcal{L}^2 - \epsilon_4^2} \approx \frac{\epsilon_4^2}{2\mathcal{L}}$$

$$\epsilon_+ \equiv \sqrt{\epsilon_0^2 + \mathcal{L}^2 + 2\mathcal{L}\epsilon_0} = \sqrt{(\epsilon_0 + \mathcal{L})^2} = \mathcal{L} + \sqrt{\mathcal{L}^2 + \epsilon_4^2} \approx 2\mathcal{L}$$

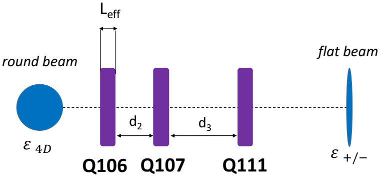
Emittance ratio or "flatness":

$$\frac{\epsilon_+}{\epsilon_-} = \frac{4\mathcal{L}^2}{\epsilon_u^2} = \frac{1}{p_z^2} e^2 B_{0z}^2 \frac{\sigma_0^2}{\sigma_0'^2}$$

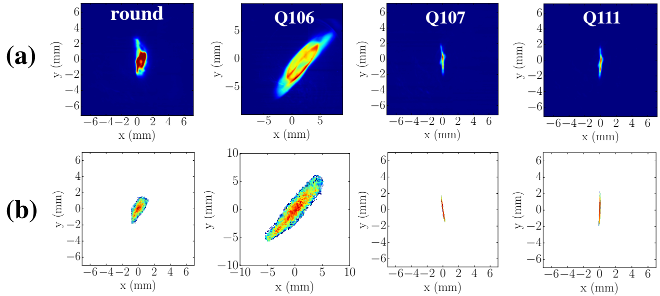
Example calculation: $\sigma_+ = \sqrt{\beta_{x,y}\epsilon_+} \rightarrow \epsilon_4{=}2\ \mu$m $\rightarrow \epsilon_+ = 40\mu$m, $\epsilon_- = 0.1\mu$m $\rightarrow \beta_{x,y} = 8$m, $\sigma_+ = 1.8$mm and $\sigma_- = 0.09$mm

Burov, A., Phys. Rev. E ***66***, *016503 (2002)*
Kim, KJ., PRSTAB, ***6***, *104002 (2003).*

Round-to-flat transformation



- Q106,Q107,Q111 - skew-quadrupoles
- (a) - Experimental, (b) - Simulations in Impact-T



Good agreement - good model!

RTFB solutions (thin lens)

FAST quadrupoles: $K = (10.135 \times 40\, I_q)/(1.8205 \times p\,[MeV/c])$,
$L_{eff} = 17cm$

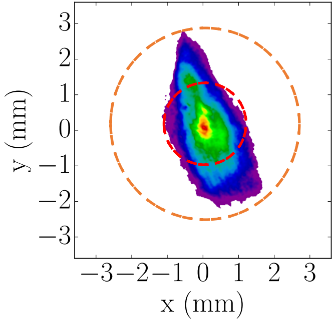
$$q_1 = \pm\sqrt{\frac{-d_2(d_T s_{21} + s_{11}) + d_T s_{22} + s_{12}}{d_2 d_T s_{12}}},$$

$$q_2 = \frac{(d_2 + d_3)(q_1 - s_{21}) - s_{11}}{d_3(d_2 q_1 s_{11} - 1)},$$

$$q_3 = \frac{d_2(q_2 - q_1 q_2 s_{12}) - s_{22}}{d_2(d_3 q_2 s_{22} + q_1 s_{12} - 1) + d_3(s_{12}(q_1 + q_2) - 1)}$$

Numerical optimization can be used for correcting (q_1, q_2, q_3) for chromaticities and other second order effects

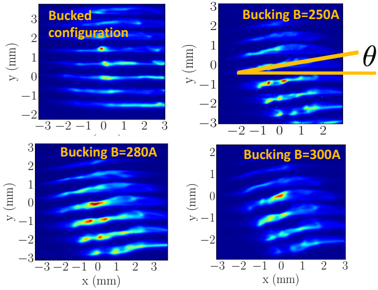
What if beam is not round?

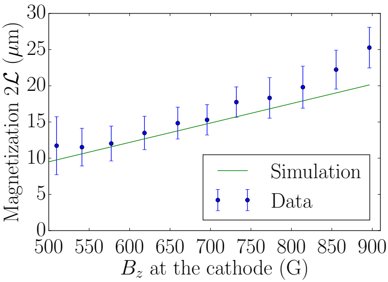


FAST laser cathode distribution
$\sigma_x = 520\mu$m, $\sigma_y = 920\mu$m
First flat beam with *asymmetric* laser!

1. Assume very low charge (20 pC) $\rightarrow$ no space charge. RTFB solutions do not depend on $\mathcal{L}$. White areas will be not present in the final phase space.
2. When space charge is included, the problem requires 4 skew quadrupoles in RTFB setup
3. FAST Run 2017 used 3 magnets, will add additional in the future

CAM measurement with slits

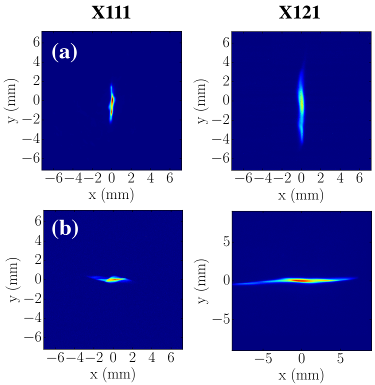




- $< L >= 2p_z\frac{\sigma_1^2 M \sin\theta}{D}$, where p_z is momentum, D is the drift length, $\sigma_1 = (n-1) * d/5$, $M = \sigma_2/\sigma_1$ - magnification factor
- First used in Fermilab A0 flat beam experiment (Sun, et. al.)
- Similar idea with multi-beam generated by MLAs (Halavanau, et.al, Phys. Rev. AB, **20**, 10, 103404, (2017))

Vertical/Horizontal flat beams

Q = 20 pC, B_z=730 Gauss

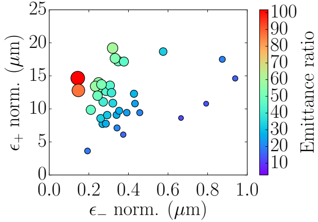


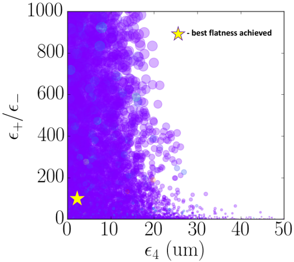
X111/X121 - screens 4 m apart downstream of RTFB

- Vertical flat beam $\epsilon_- \to \epsilon_x$, RTFB: + - +
- Horizontal flat beam $\epsilon_- \to \epsilon_y$, RTFB: - + -
- Beam-based optimizer: optimizing projections/ratio (not very efficient because $\sigma = \sqrt{\beta\epsilon}$)
- Emittances: (2 nm, 220 nm) geom., both hfb/vfb
- How to further optimize the emittance?

FAST flat beam parameter space

(*left*) Experimental flat beam realizations at FAST. Size/color of circles defines aspect ratio. First automatic RTFB transformation!



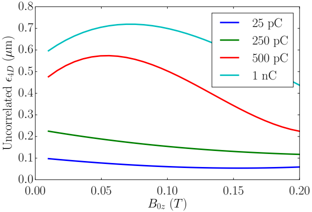


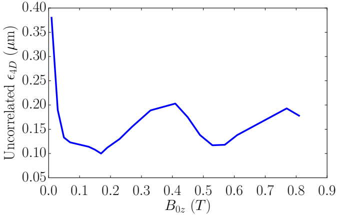
(*right*) 100,000 realizations of genetic optimization algorithm (MOGA). Optimizing flatness using: gun phase, gun gradient, CAV1/CAV2 parameters, spot size and solenoidal fields as variables (path to AI phase-space manipulation w/ Auralee Edelen).

Further optimization

Idea by S. Nagaitsev:

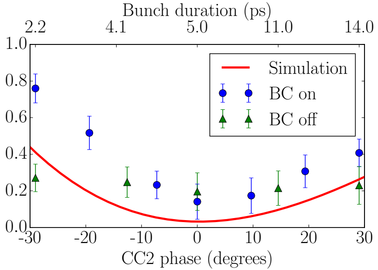
Can we compensate space-charge with strong field?



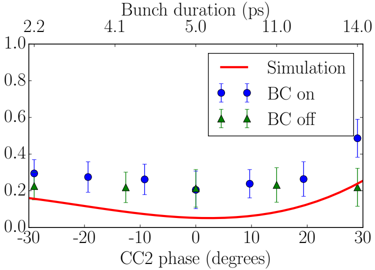


Preliminary cathode design considerations *in progress*!

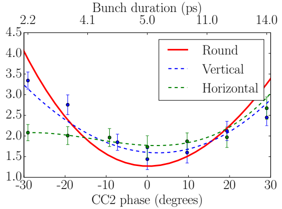
First compressed flat beams!



Compressed vertical flat beam - significant emittance growth at maximum compression



Horizontal flat beam - small emittance in the same plane as chicane CSR, slight growth (Zhu, 2014)



- Horizontal flat beam emittance is largely unaffected by chicane CSR
- Total $(\epsilon_x \epsilon_y)$ preserved better

Flat beam summary

1. Generated CAM/flat beam from asymmetric laser (**NEW**)
2. Automatic horiz./vert. flat beam transformation (**NEW**)
3. Lowest emittance 0.1 μm (below thermal) (**NEW**)
4. Compressed flat beams, helps with beam transport (**NEW**)
5. AI phase-space manipulations (**NEW, in progress**)
6. Getting closer to ILC-type beam (**NEW, in progress**)
7. New comprehensive image analysis tool

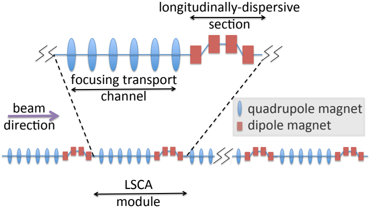
<u>Future of flat beams at FAST:</u>

1. High-charge flat beams (with J. Rosenzweig)
2. Additional diagnostics $\rightarrow$ improve emittance ratio
3. Radiation generation at FAST (channeling, dielectric)

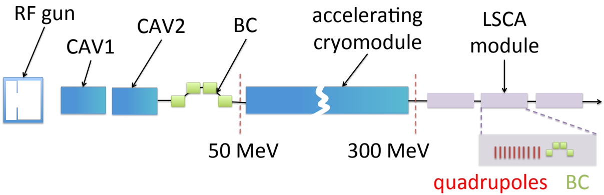
Longitudinal space-charge amplifier

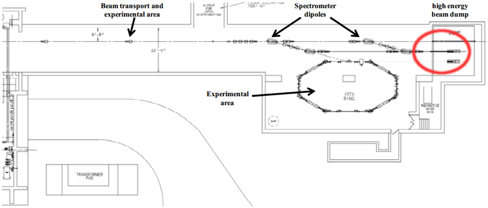
- Longitudinal space charge effects are responsible for unwanted energy modulations and emittance growth in FELs
- Can we take advantage of them?*
- The technique was recently demonstrated in the optical domain**

*M. Dohlus, E. A. Schneidmiller, and M. V. Yurkov, *Phys. Rev. ST Accel. Beams*, **14**, *090702 (2011).*
A. Marinelli, et al., *Phys. Rev. Lett.*, **110, *264802 (2013).*



Possible location at FAST





Possible use of the FAST beamline before the high-energy adsorber area

Space charge calculation

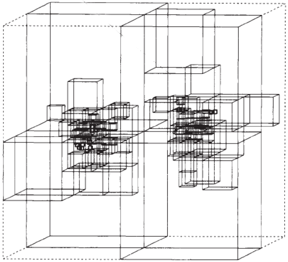
- Many numerical and analytical methods “reduce” the space charge problem’s complexity which ultimately limits the maximum attainable spatial resolution
- Most of the LSC studies use a simple 1D model based on impedance approximation
- Space charge problem is very similar to the well-known N-body problem in celestial mechanics
- **We used very effective algorithm for the gravitational N-body problem, so called “tree” or Barnes-Hut (BH) algorithm***

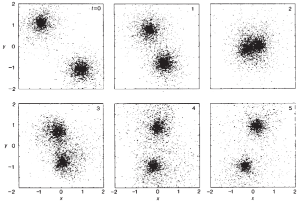
Some conventional codes: ASTRA, SYNERGIA, TSTEP

*J. Barnes and P. Hut, *Nature*, **324**, *446 (1986)*.

Tree algorithm: in brief

- Scales as $\mathcal{O}(N \log N)$, where N is the number of macroparticles used to represent the beam
- Precision parameter corresponds to the “depth” of the tree
- Can be applied to many-body systems

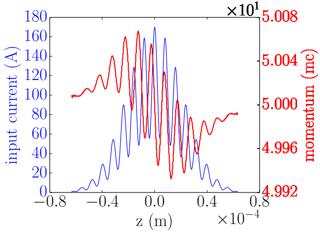


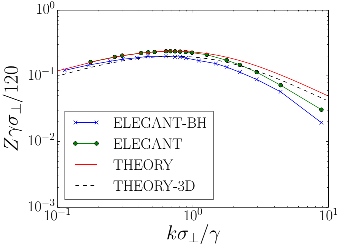


Images courtesy of J. Barnes

Code validation

Let's consider initial bunch distribution with pre-modulated current profiles of the form $\boldsymbol{f(\mathrm{r}) = T(x,y)L_z(z)\,[1 + m\cos kz]}$





On the left: Initial density modulation resulted in energy modulation. *On the right:* The agreement between the BH algorithm and analytical impedance equation

$$\boldsymbol{Z(k) = -i\frac{Z_0}{\pi\gamma\sigma}\frac{\xi_\sigma}{4}e^{\xi_\sigma^2/2}\mathrm{Ei}(-\frac{\xi_\sigma^2}{2})}$$

Bunching factor and gain

To characterize the current (density) modulation one can introduce the bunching factor

$$b(\omega) = \frac{1}{N} \left| \sum_n \exp(-i\omega t_n) \right|$$

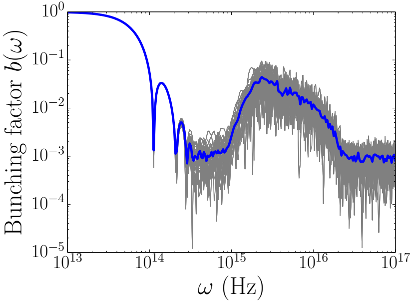
The broadband amplification process can be seen on the bunching factor curve as a broad peak. One can numerically compute the gain as:

$$G(\omega) = G_1 \times G_2 \times \ldots \times G_n = \left| \frac{b_f(\omega_f)}{b_0(\omega_i)} \right|$$

*JLAB-TN-14-016, Rui Li and C.-Y. Tsai

Bunching factor (averaged)

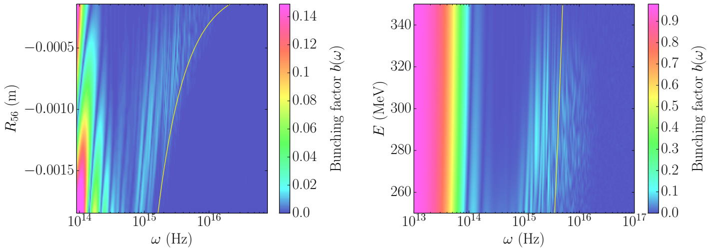
The LSC impedance results in selection of preferred frequency



100 realizations with 1M particles (gray traces) and corresponding average (blue trace)

$b(\omega)$ as a function of E and chicane

On the left: Bunching factor for different values of the chicane long. dispersion R_{56}



On the right: The change of the bunching factor vs energy of the bunch

Yellow solid line is analytical prediction.

More results: A. Halavanau and P. Piot, NIM A 2016 819 144-153.

Desired bunch parameters

Parameter	**Value**	**Units**
Spotsize, σ	2.2 - 70.4	μm
Charge, Q	20.0	pC
Lorentz factor, γ	50 - 1000	–
Bunch duration, τ	120	fs
Norm. transv. emittance, $\varepsilon_{x,y}$	10^{-8}	m
Momentum spread, σ_δ	10^{-4}	–
Total LSCA length, D	28.0	m

LSCA at FAST Summary

- Using a gridless code adapted from Astrophysics we have investigated effects in the LSC impedance and found that the one-dimensional often used LSC impedance model is a good approximation **(NEW)**
- Will not require much redesign of the lattice, can be compact (10-20 m), also will help to turn FAST injector into FEL
- We demonstrated that LSCA can produce femtosecond pulses of light in optical regime. Still needs to be pushed for the VUV regime **(NEW)**

Final conclusions

1. Existing analytical model of 1.3 GHz accelerating SRF cavity confirmed, backbone of ILC, LCLS-II
2. Developed MLA based laser transverse shaping technique, significantly improved beam emittance
3. Generated CAM and flat beams at FAST, on way to ILC-type beams
4. Generated tunable bunch trains with MLA+EEX, many outcomes
5. Had a lot of fun

Fermilab Accelerator PhD program

Vita: 3 papers + 2 in progress

1. Simulation of a cascaded longitudinal space charge amplifier for coherent radiation generation, NIMA, 819, (2016) 144-153
2. Analysis and Measurement of the Transfer Matrix of a 9-cell 1.3-GHz Superconducting Cavity, Phys. Rev. Accel. Beams 20, 4, 040102 (2017)
3. Spatial control of photoemitted electron beams using a microlens-array transverse-shaping technique, Phys. Rev. Accel. Beams 20, 103404 (2017)
4. Magnetized and flat beam experiment at FAST, IPAC2018, *paper in progress*
5. Simple technique for a tunable bunch train generation, IPAC18, *paper in progress*
6. **17 conference papers (first author)**

Credits

Acknowledgements:

- P. Piot (NIU, Fermilab) for supervising this research
- S. Nagaitsev, A. Valishev and V. Shiltsev, C. Thangaraj (Fermilab) for valuable suggestions
- A. Romanov (Fermilab) for his help with beam alignment at FAST and useful comments
- J. Power (ANL, AWA), G. Ha (POSTECH) for their significant contribution to the MLA research
- D. Ratner and Zh. Huang (SLAC) for interest in MLA applications
- A. Edelen (Fermilab/Colorado State, for interest in optimizers and neural network flat beam generation)

Thank you for your attention!